First Results from the Shellflow Survey

Stéphane Courteau[1], Jeffrey A. Willick[2], Michael A. Strauss[3], David Schlegel[3], Marc Postman[4]

(1) Herzberg Institute of Astrophysics, Victoria, BC

(2) Stanford University, Department of Physics, Stanford, CA

(3) Princeton University Observatory, Princeton, NJ 08544

(4) Space Telescope Science Institute, Baltimore, MD

Abstract. We present preliminary results from the Shellflow program, an all-sky Tully-Fisher (TF) survey of 297 Sb−Sc with redshifts between 4000 and 7500 $\mathrm{km\,s}^{-1}$. The program was designed to ensure uniformity of the data between observing runs and between telescopes, thereby eliminating the possibility of a spurious bulk flow caused by data inhomogeneity. A simple bulk flow model suggests that the Shellflow galaxies are nearly at rest with respect to the cosmic microwave background (CMB). Taken at face value, this result suggests that most of the ~ 600 $\mathrm{km\,s}^{-1}$ motion of the Local Group with respect to the CMB is due to material within $\sim 60\,h^{-1}\mathrm{Mpc}$ — a striking confirmation of the gravitational instability picture and the notion of homogeneity in the Universe. Differences between our Shellflow "null" result and claims of larger bulk motions based on analyses of the MarkIII catalog are possibly due to small inhomogeneities between the sub-samples in MarkIII. Our preliminary Shellflow bulk velocity, $V_{bulk} = 80 \pm 150$ $\mathrm{km\,s}^{-1}$ in the CMB frame, must still be refined with Monte-Carlo simulations and tidal field analysis.

1.   Introduction

It is of great cosmological importance to identify the volume of space, centered on the Local Group, which is at rest with respect to the CMB. Very large scale fluctuations are required to move ever larger volumes of space in the standard gravitational instability model. In standard Cold Dark Matter cosmologies, the volume of space bounded by the nearest superclusters (Great Attractor, Pisces-Perseus, Coma) is expected to define an inertial frame nearly at rest with respect to the CMB. The distribution of the matter within this volume should explain the ~ 600 $\mathrm{km\,s}^{-1}$ motion of the Local Group in the CMB frame. The detection of a large amplitude ($V_{bulk} \gtrsim 700$ $\mathrm{km\,s}^{-1}$) on scales exceeding 8000 $\mathrm{km\,s}^{-1}$ by Lauer & Postman (1994), followed by recent measurements with similar amplitude by Willick (these proceedings) and the SMAC team (Smith, these proceedings), have not only challenged the notion that the bulk flow on large scales is small, but have also pushed cosmological models to the breaking point.

Moreover, there are contradictory claims for the observed bulk flow within a sphere of 6000 km s^{-1}, and whether it is generated by internal or external mass fluctuations. The most recent POTENT reconstruction of the MarkIII velocities (Dekel $et~al.$ 1999) found a bulk velocity within 6000 km s^{-1} of 370 ± 125 km s^{-1} in the CMB frame towards Supergalactic $(L, B) = (165°, -10°)$. Dekel $et~al.$ (1999) argue that this motion is generated by the $external$ mass distribution on very large scales (see also Courteau $et~al.$ 1993). However, other investigations using nearly homogeneous samples of galaxies within and beyond $\sim 60\,h^{-1}$Mpc find motion consistent with the amplitude and direction of the CMB dipole (Giovanelli, these proceedings). New local peculiar velocity measurements based on the brightness of supernovae Type Ia (Riess, these proceedings) and surface brightness fluctuations (Tonry and Dressler, these proceedings) are also consistent with little bulk motion at $60\,h^{-1}$Mpc. This suggests that the reflex motion of the Local Group could be explained by material contained $within$ $60\,h^{-1}$Mpc.

The controversy over the observed bulk flow within $60\,h^{-1}$Mpc stems, in large part, from our inability to combine the various galaxy distance samples used in flow studies into a single homogeneous catalog. None of the surveys within $60\,h^{-1}$Mpc had sampled the $entire$ sky uniformly[1]. In an effort to overcome this situation, we devised a new study that would take advantage of Northern and Southern NOAO facilities to map the motions of a shell of galaxies with significant overlap between the hemispheres, and with existing peculiar velocity surveys. Our new "$Shellflow$" survey was designed to provide $precise$ and $uniform$ photometric and spectroscopic data over the whole sky, and thus to remove the uncertainties associated with matching heterogeneous data sets. With Shellflow, and further calibration of existing TF data sets, we expect a high-accuracy detection of the bulk flow amplitude and a better constrained characterization of the tidal field at 6000 km s^{-1}.

2.   Observational Strategy

The Shellflow sample is drawn from the Optical Redshift Survey sample of Santiago $et~al.$ (1995; ORS). The ORS sample consists of all galaxies in the UGC, ESO, and ESGC Catalogs with $m_{\mathrm{B}} \leq 14.5$ and $|b| \geq 20°$. We initially selected all non-interacting Sb and Sc galaxies in the ORS with redshifts[2] between 4000 and 7500 km s^{-1}, inclinations between $45°$ and $78°$, and with Burstein-Heiles (1982) extinctions $A_B \leq 0^{m}\!.30$. This produced a catalog of more than 300 objects. All galaxies were then visually inspected on the Digitized POSS plates; those with bright foreground stars and obvious disturbances were excluded, yielding a final sample of 297 Shellflow galaxies. No pruning was done of galaxies not matching idealized morphologies beyond the restriction on Hubble type and inclination.

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[1]Earlier attempts include David Schlegel and Josh Roth's thesis work.

[2]We actually define three subsamples complete in that range with different definitions of redshift: measured in the Local Group frame, the CMB frame, and after correction for peculiar velocities according to the $IRAS$ model of Yahil $et~al.$ (1991) with $\beta = 1$; if we chose only one of them, the sample would decrease in size by 20%.

The data were collected between March 1996 and March 1998 at NOAO, using V and I-band photometry and Hα rotation curves. Data taking and reduction techniques follow the basic guidelines of previous optical TF surveys (*e.g.* Courteau 1996, 1997; Schlegel 1995). The V and I-band imaging was obtained at the CTIO and KPNO 0.9m telescopes. The photometric calibration is based on the Kron-Cousins system; data taken on nights with standard star photometric scatter greater than $0\overset{m}{.}020$ were excluded. The Kron-Cousins system also allows direct matching with two largest I-band TF samples to date (Mathewson *et al.* 1992, Giovanelli *et al.* 1998). The Hα spectroscopy was obtained mostly in photometric conditions with the RC spectrographs at the CTIO and KPNO 4m telescopes. Typical integrations were ~ 900s and ~ 1800s for imaging and spectroscopy respectively.

Forty-one galaxies were imaged at both CTIO and KPNO, and we have repeat imaging from a given telescope for 106 galaxies. In addition, we observed 27 galaxies spectroscopically from both CTIO and KPNO, and obtained duplicate spectra from a given telescope for 38 galaxies. The total magnitudes and rotational line widths reproduce to within $0\overset{m}{.}06$ and $3\ \mathrm{km\,s^{-1}}$ (rms deviations) respectively, with no systematic effects seen between hemispheres or between runs. Moreover, all data reduction was done independently by Courteau and Willick using different software and methodology; the results between the two agree to within the errors quoted above. The high level of accuracy in our Shellflow data meets our requirement for a measurement of a significant bulk flow result.

3.   Analysis and Results

Following the approach of Lauer & Postman (1994), we use the sample itself to calibrate the distance indicator relation; this mitigates the need to tie the sample to external TF calibrators such as clusters (although it precludes measurement of a monopole term in the velocity field). We choose the "inverse" form of the TF relation, which makes Malmquist and selection bias effects negligible (cf., Strauss & Willick 1995). A maximum likelihood analysis for a pure Hubble expansion model (no bulk flow) allows us to constrain σ^{int}, the intrinsic TF scatter, and δv, the typical error in measuring raw rotation velocities. We hardwire σ_{phot}, the total error associated with photometry (including inclination errors), to 0.15 mag, which is a small fraction of the error budget. Two other parameters constrain the dependence of the TF relation on surface brightness and shape of the rotation curve. The best TF fit is achieved for V_{rot} measured near 1.7 disk scale lengths, similar to but somewhat smaller than the values found by Courteau (1997) and Willick (1999). A small surface brightness dependence is also found for the optimized TF relation, although this could be induced by the particular choice of luminosity profile fitting that we have adopted (see also the discussion by Willick [LP10K], these proceedings; Courteau *et al.* 2000).

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Shellflow TF Relation

$\sigma \approx 0.37$ mag

$\eta = \log(2v_{TF}) - 2.5$

$\eta = -0.124(M_{eff} + 20.96)$

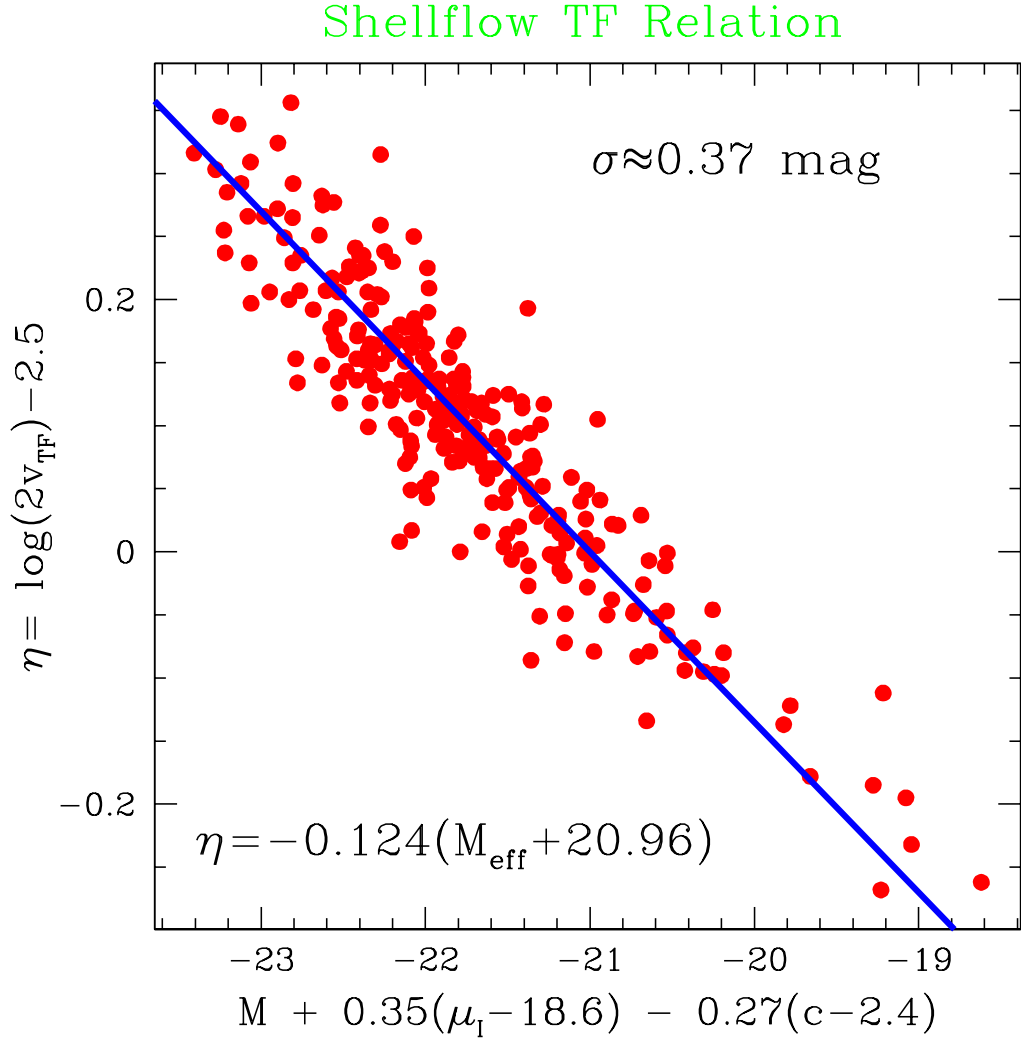$M + 0.35(\mu_{I} - 18.6) - 0.27(c - 2.4)$

Figure 1. Tully-Fisher calibration of the Shellflow sample. This figure includes all 297 Shellflow galaxies. The slope and scatter are comparable to current modern I-band TF investigations. The absolute magnitudes are corrected for the small surface brightness and concentration index dependences of the TF relation. As mentioned in the text, the reality of these dependences is still under investigation by ourselves and other workers. The results of our flow fits are, however, independent of whether or not these additional correlations are included.

For this analysis, we adopt a model of **Hubble expansion plus a bulk flow** to compute absolute from apparent magnitudes:

$$d(\text{Mpc}) = \frac{1}{H_0} \left(cz - \mathbf{V}_B \cdot \hat{\mathbf{n}}\right) ,$$

where $H_0 = 100$ km s^{-1} Mpc^{-1} and cz is the measured redshift in km s^{-1}. We measure cz in either the **CMB** frame or the **LG** frame. (A different choice of Hubble constant would shift the zero point of the derived TF relation but would have no effect on our bulk flow fits.)

The TF fit slope and scatter are comparable to recent I-band investigations (*e.g.* Giovanelli *et al.* 1998). The Shellflow TF relation is shown in Fig. 1. We find no dependence of the internal extinction correction on luminosity, and the TF parameters are virtually unchanged whether one adopts Burstein-Heiles (BH), or Schlegel, Finkbeiner, & Davis 1998 (SFD) Galactic extinctions. The optimization with respect to all TF parameters and bulk flow velocity components $(\mathrm{V}_x, \mathrm{V}_y, \mathrm{V}_z)$, yields the following fits:

Table 1.   **Best-fit Velocity Components (km s^{-1})**

SFD extinctions
V_z	V_x	V_y	Frame
47.5	−37.7	28.6	CMB
−257.1	−98.9	566.1	LG

BH extinctions
V_z	V_x	V_y	Frame
58.8	−38.0	46.6	CMB
−242.6	−99.2	584.5	LG

The typical velocity errors, computed by holding the other parameters fixed, are $\Delta\mathrm{V}_x = \pm110$ km s^{-1}, $\Delta\mathrm{V}_y = \pm90$ km s^{-1}, $\Delta\mathrm{V}_z = \pm70$ km s^{-1}, for an upper limit on the total amplitude equal to $\Delta\mathrm{V} \leq 150$ km s$^{-1}(1\sigma)$. Numerical simulations to assess the full covariance matrix of the errors will be presented elsewhere.

Modelling the Shellflow galaxy peculiar velocities with a Hubble expansion and a bulk flow, one finds a low bulk motion of 80 ± 150 km s^{-1} with respect to the CMB. Correspondingly, the Shellflow volume moves at ~ 600 km s^{-1} in the frame of the LG[3]. This corresponds to the reflex motion of the Local Group motion with respect to the CMB. The directional components of the flow are poorly constrained since its amplitude is so low.

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[3]See Courteau & van den Bergh (1999) for caveats regarding transformations to the Local Group reference frame.

Velocity Residuals, CMB Frame

✳ 1500 km/s

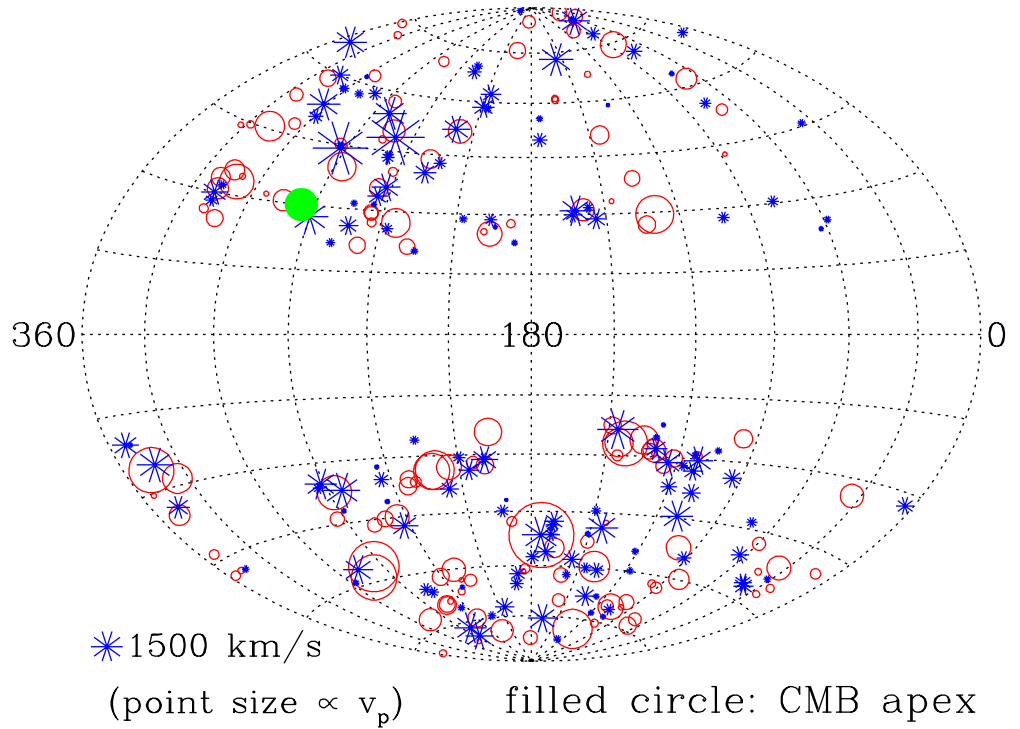(point size ∝ v_p)   filled circle: CMB apex

Figure 2.   Plot of peculiar velocities in the CMB frame. The point size is proportional to the velocity amplitude, as indicated by the key at the lower left. The circles and asterisks represent inflowing and outflowing objects, respectively. The two point types are well-mixed at all positions on the sky, indicating the absence of any significant bulk flow in the CMB frame.

Our result is in agreement with other newly-presented results at this workshop, derived from surface brightness fluctuation techniques (Tonry & Dressler; $V_{bulk} = 289 \pm 137$ km s^{-1} at 3000 km s^{-1}), nearby SNIa (V_{bulk} consistent with zero at 6000 km s^{-1} (Riess, these proceedings), and previous TF analyses by Giovanelli and collaborators. Taken together these results suggest that most of the mass responsible for the motion of the LG lies within 6000 km s^{-1}. Thanks to many new peculiar velocity surveys, the picture of cosmological bulk flows seems to imply "convergence" of the flow field within 6000 km s^{-1} to the CMB dipole value. However, this simple picture is challenged by a mix of low and high amplitude bulk flow measurements on larger scales. If the flow is nearly quiet at $\sim 6000 - 7000$ km s^{-1}, one is hard-pressed to explain the reported high amplitude flows on larger scales. These issues are discussed elsewhere in these proceedings.

4. The MarkIV Catalog of Galaxy Peculiar Velocities

Two of us (JW & SC + collaborators) have recently combined the major distance-redshift surveys from both hemispheres (published before 1994) into a catalog of 3100 galaxies (Willick *et al.* 1997, the "MarkIII Catalog"). However, full homogenization at the $2 - 3\%$ level, the minimum required for an accurate bulk flow detection at 6000 km s^{-1}, was not achieved in MarkIII due to irreducible uncertainties associated with matching disparate TF datasets. Furthermore, a revised calibration of the MarkIII TF zero-points based on maximal agreement with the peculiar velocities predicted by the IRAS 1.2Jy redshift survey suggests a possible source of systematic error for the data sets which cover the PP cone (Davis, Nusser, & Willick 1996, Willick & Strauss 1998 [VELMOD]). This uncertainty has not seriously affected mass density reconstructions (Dekel *et al.* 1999) but it could lead to spurious estimates of the bulk flows on larger scales.

MarkIII was originally tied to the North/South cluster calibration of Han & Mould (1992). We now plan a revised MarkIV calibration based on Shellflow. Because of the overlap with existing surveys at comparable depth, Shellflow will be of fundamental importance in tying these datasets together in a uniform way. With this more accurate global calibration, we expect that the MarkIV catalog will be better suited than its predecessors for studying the velocity and density fields in the local universe.

5. Summary

- The Shellflow velocity components in the CMB frame are small. *There is no significant bulk motion of the Shellflow sample relative to the CMB.*

- The Shellflow velocity components are large when the fit is done in the LG frame. This represents the reflex of the LG motion with respect to the CMB.

- Results are insensitive to BH versus SFD Galactic extinctions.

- The Shellflow bulk motion reported here has not been fully tested against Monte-Carlo simulations or using a complete tidal field analysis. A comprehensive study is under way.

References

Burstein, D., & Heiles, C. 1982, AJ, 87, 1165 (BH)

Courteau, S. 1996, ApJS, 103, 363

Courteau, S. 1997, AJ, 114, 2402

Courteau, S., Faber, S.M., Dressler, A., & Willick, J.A. 1993, ApJ, 412, L51

Courteau, S., & van den Bergh, S. 1999, AJ, 118, 337

Courteau, S. *et al.* 2000, in preparation

Davis, M, Nusser, A., & Willick, J. A., 1996, ApJ, 473, 22

Dekel, A., Eldar, A., Kolatt, T., Yahil, A., Willick, J. A., Faber, S. M., Courteau, S., & Burstein, D. 1999, ApJ, 522, 1

Giovanelli, R., Haynes, M.P., Freudling, W., da Costa, L. N., Salzer, J.J., & Wegner, G. 1998, ApJ, 505, L91

Han, M.-S., & Mould, J. R. 1992, ApJ, 396, 453

Lauer, T. R., & Postman, M. 1994, ApJ, 425, 418

Mathewson, D. S., Ford, V. L, & Buchhorn, M. 1992, ApJS, 81, 413

Santiago, B. X., Strauss, M. A., Lahav, O., Davis, M., & Huchra, J. P. 1995, ApJ, 446, 457

Schlegel, D. 1995, PhD. Thesis, University of California

Schlegel, D., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525 (SFD)

Strauss, M.A., & Willick, J.A. 1995, Physics Reports, 261, 271

Willick, J.A. 1999, ApJ, 516, 47

Willick, J.A., & Strauss, M.A. 1998, ApJ, 507, 64

Willick, J. A. *et al.* 1997, ApJS, 109, 333

Yahil, A., Strauss, M. A., Davis, M., & Huchra, J. P. 1991, ApJ, 372, 380